Cosmological neutrinos after Planck

Jan Hamann

CERN

Workshop on the Origin
of Neutrino Mass —
From Majorana to LHC

ICTP Trieste, 2-5 Oct 2013

Planck at a glance

esa

planck

cnes

agenzia spaziale italiana

NASA

cnrs

DTU Space
National Space Institute

ISTITUTO NAZIONALE DI ASTROFISICA
INAF

Science & Technology Facilities Council

CSIC
Consejo Superior de Investigaciones Científicas

National Research Council of Italy

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN

CSA ASC

DLR
Deutsches Zentrum für Luft- und Raumfahrt e.V.

UK SPACE AGENCY

MAX-PLANCK-GESELLSCHAFT

HFI PLANCK

PLANCK LFI

IAS orsay

IAP

INAF - IASF BO
ISTITUTO NAZIONALE DI ASTROFISICA
ISTITUTO DI ASTROFISICA SPAZIALE E FISICA COSMICA DI BOLOGNA

A" Aalto University

Kavli Institute for Cosmology Cambridge KICC

ioa

Cavendish Astrophysics

UNIVERSITY OF CAMBRIDGE

CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

irfu cea saclay

cea
énergie atomique • énergies alternatives

CESR

CITA–ICAT

cnrs IN2P3
Les deux infinis

ipac Infrared Processing and Analysis Center

HELSINKI INSTITUTE OF PHYSICS

INSTITUTO DE ASTROFISICA DE CANARIAS

IFCA
Instituto de Física de Cantabria

Imperial College London

Università degli Studi di Milano

NÉEL institut

IPAG

ISDC
DATA CENTRE FOR ASTROPHYSICS

JPL

LAL
LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

l'Observatoire de Paris
LERMA

LPSC Grenoble
Laboratoire de Physique Subatomique et de Cosmologie

MANCHESTER 1824
The University of Manchester

MilliLab

Max-Planck-Institut für Astrophysik

NUI MAYNOOTH

INAF
OSSERVATORIO ASTRONOMICO DI PADOVA

UNIVERSITY OF OXFORD

SAPIENZA
Università di Roma

Science & Technology Facilities Council
Rutherford Appleton Laboratory

Università degli Studi di Roma Tor Vergata

OSSERVATORIO ASTRONOMICO TRIESTE

UBC

UC
UNIVERSIDAD DE CANTABRIA

UCSB

SISSA

ALMA

ESO

US
University of Sussex

esa

UNIVERSITY OF HELSINKI

UNIVERSITÉ DE GENÈVE

UNIVERSITY OF TORONTO

UNIVERSITÉ DE PARIS-SUD XI

asdc
ASI Science Data Center

Planck at a glance

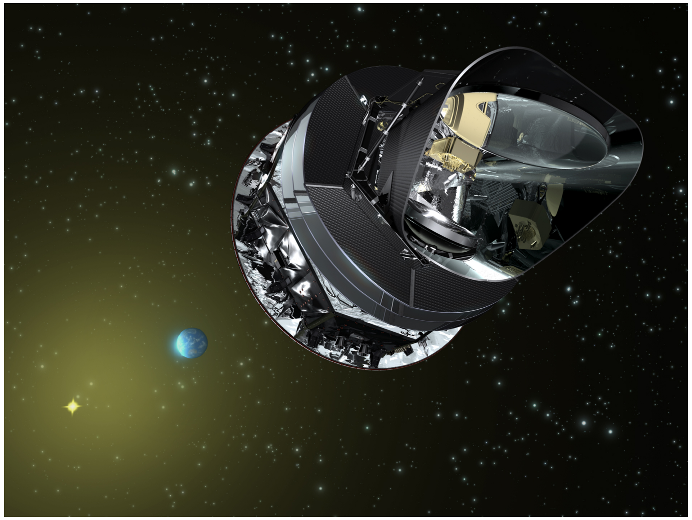
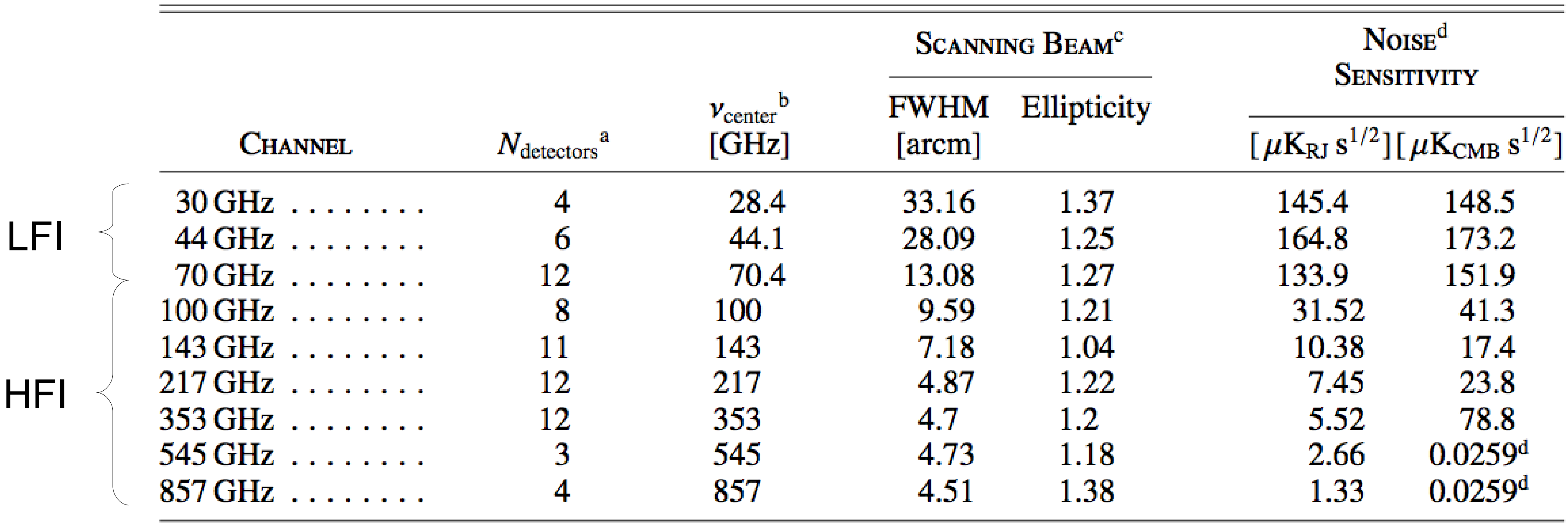
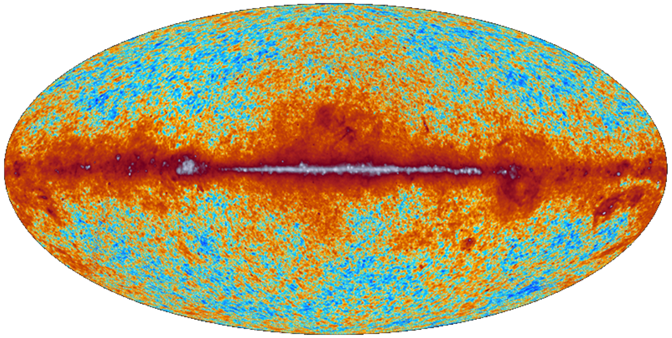


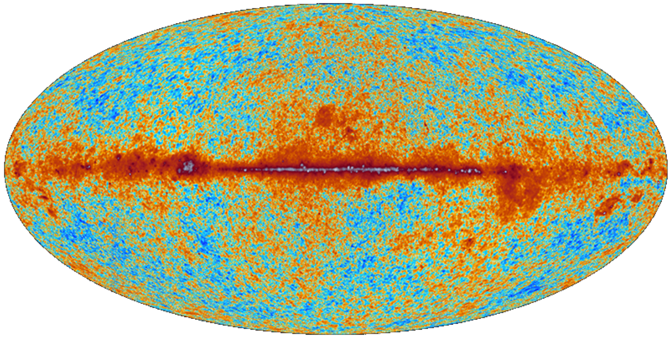
Table 2. *Planck* performance parameters determined from flight data.

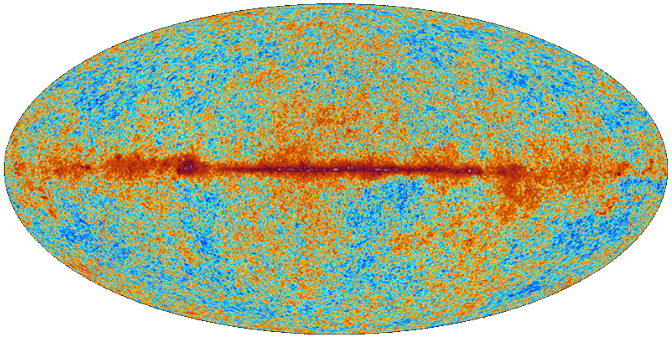


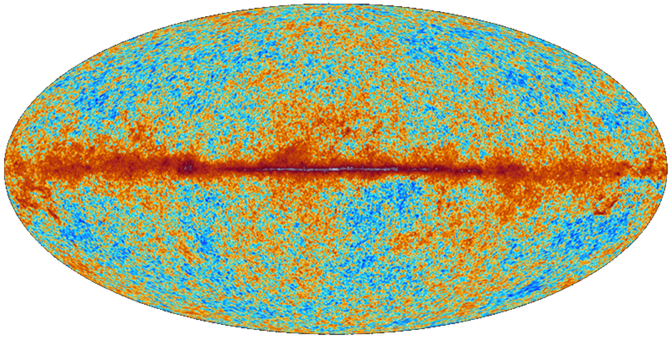
				SCANNING BEAM[c]		NOISE[d] SENSITIVITY	
	CHANNEL	$N_{\mathrm{detectors}}$[a]	ν_{center}[b] [GHz]	FWHM [arcm]	Ellipticity	[$\mu\mathrm{K}_{\mathrm{RJ}}\,\mathrm{s}^{1/2}$]	[$\mu\mathrm{K}_{\mathrm{CMB}}\,\mathrm{s}^{1/2}$]
LFI	30 GHz	4	28.4	33.16	1.37	145.4	148.5
	44 GHz	6	44.1	28.09	1.25	164.8	173.2
	70 GHz	12	70.4	13.08	1.27	133.9	151.9
HFI	100 GHz	8	100	9.59	1.21	31.52	41.3
	143 GHz	11	143	7.18	1.04	10.38	17.4
	217 GHz	12	217	4.87	1.22	7.45	23.8
	353 GHz	12	353	4.7	1.2	5.52	78.8
	545 GHz	3	545	4.73	1.18	2.66	0.0259[d]
	857 GHz	4	857	4.51	1.38	1.33	0.0259[d]

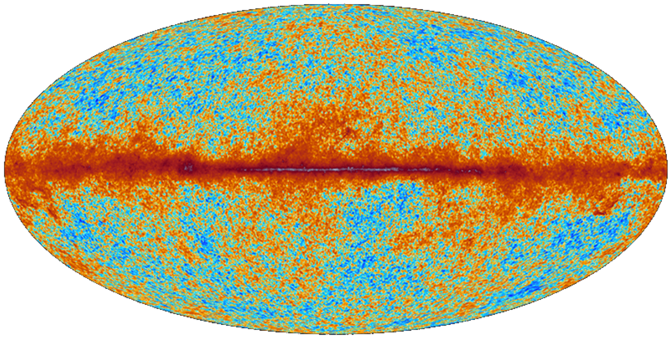
Planck's view of the microwave sky

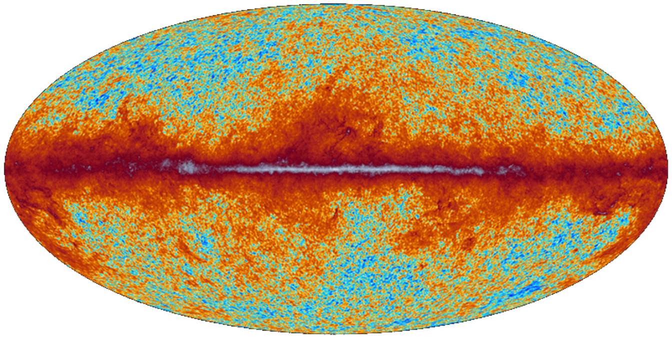

30 Ghz

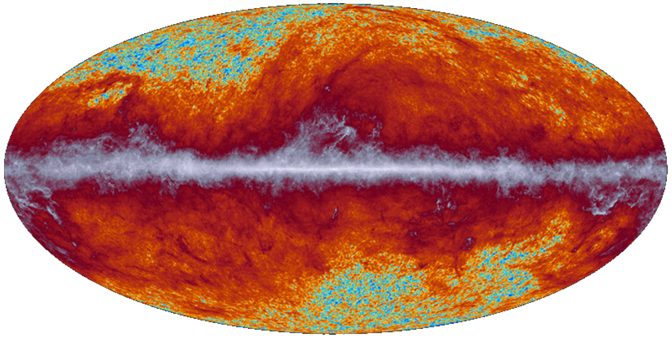

44 Ghz

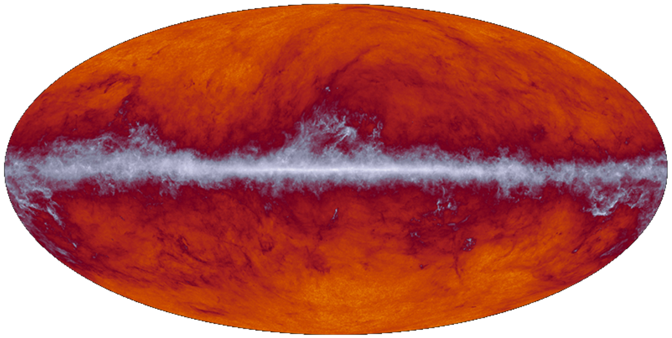

70 Ghz

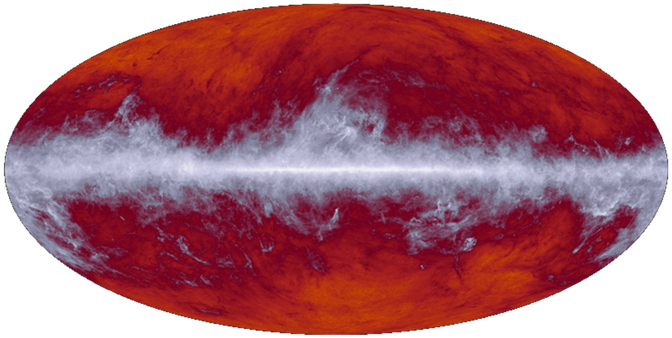

100 GHz


143 Ghz

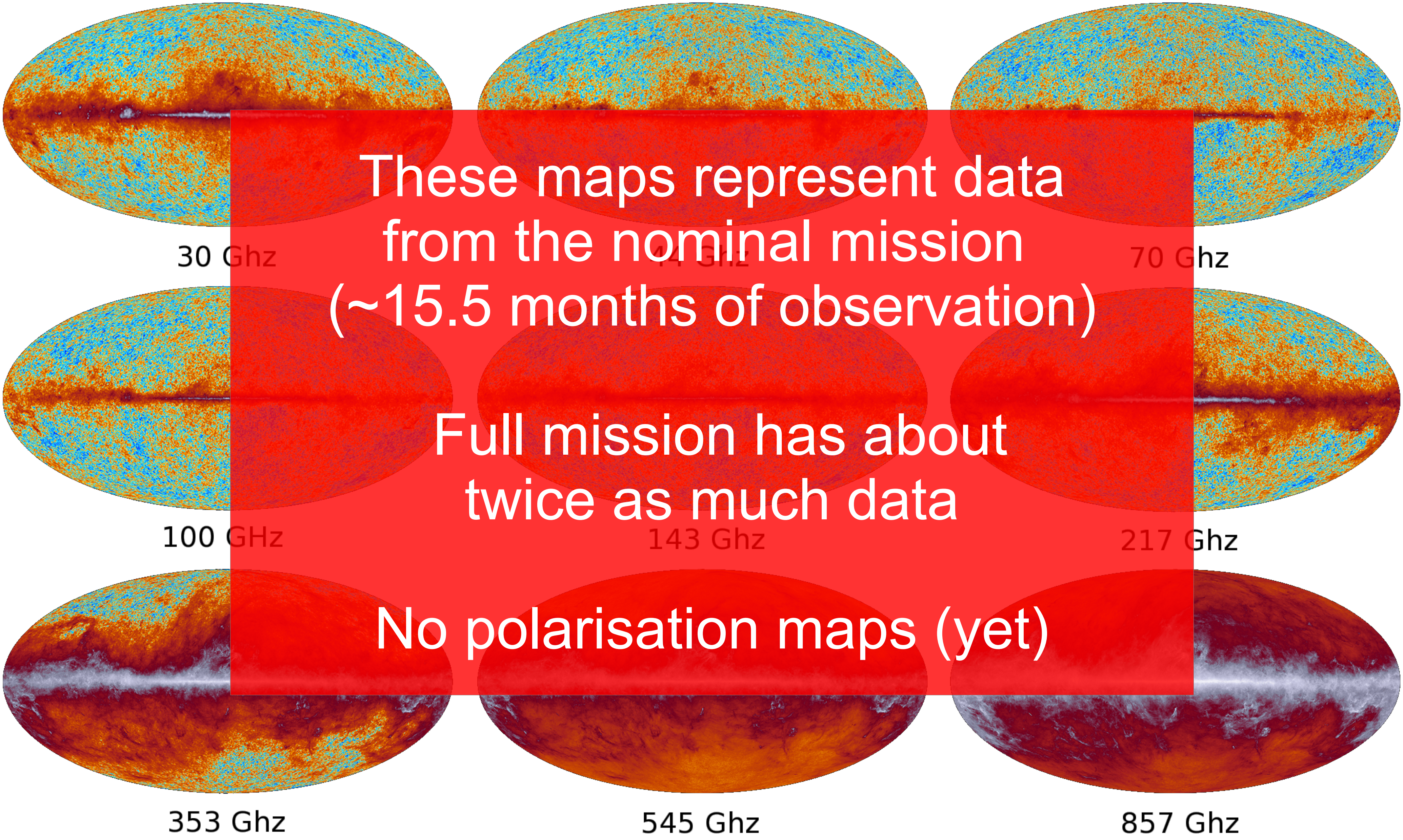

217 Ghz


353 Ghz


545 Ghz


857 Ghz

Planck's view of the microwave sky



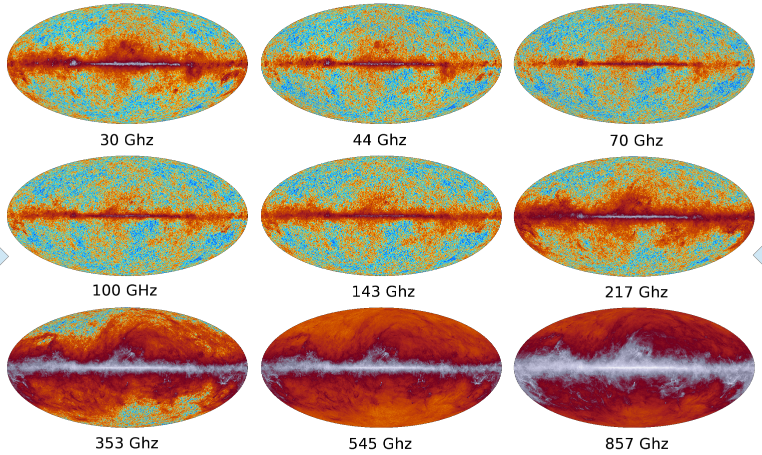
These maps represent data
from the nominal mission
(~15.5 months of observation)

Full mission has about
twice as much data

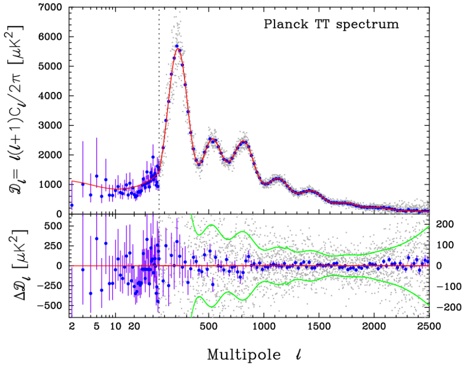
No polarisation maps (yet)

Cosmological observables

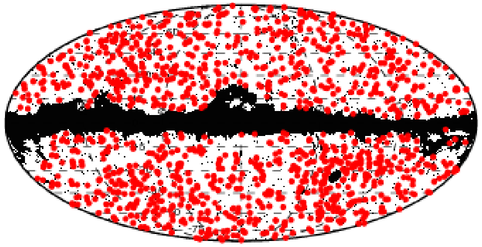
2-point correlation



SZ-effect

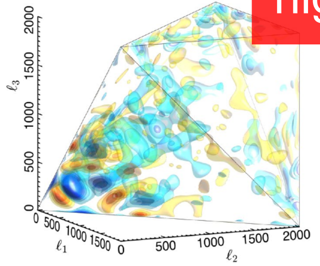


Angular power spectrum

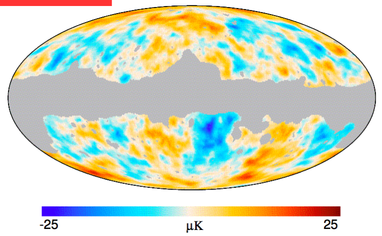


Galaxy clusters
→ cluster mass function
(when combined with
X-ray data)

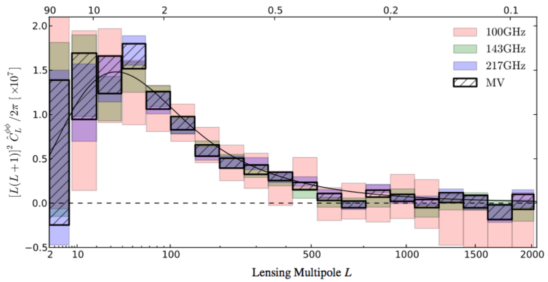
higher order correlations



Primordial non-Gaussianity



Integrated Sachs-Wolfe effect



Power spectrum of the lensing potential

What have we learnt about cosmology?

A maximally boring Universe?

☹

No real surprises, no paradigm changes

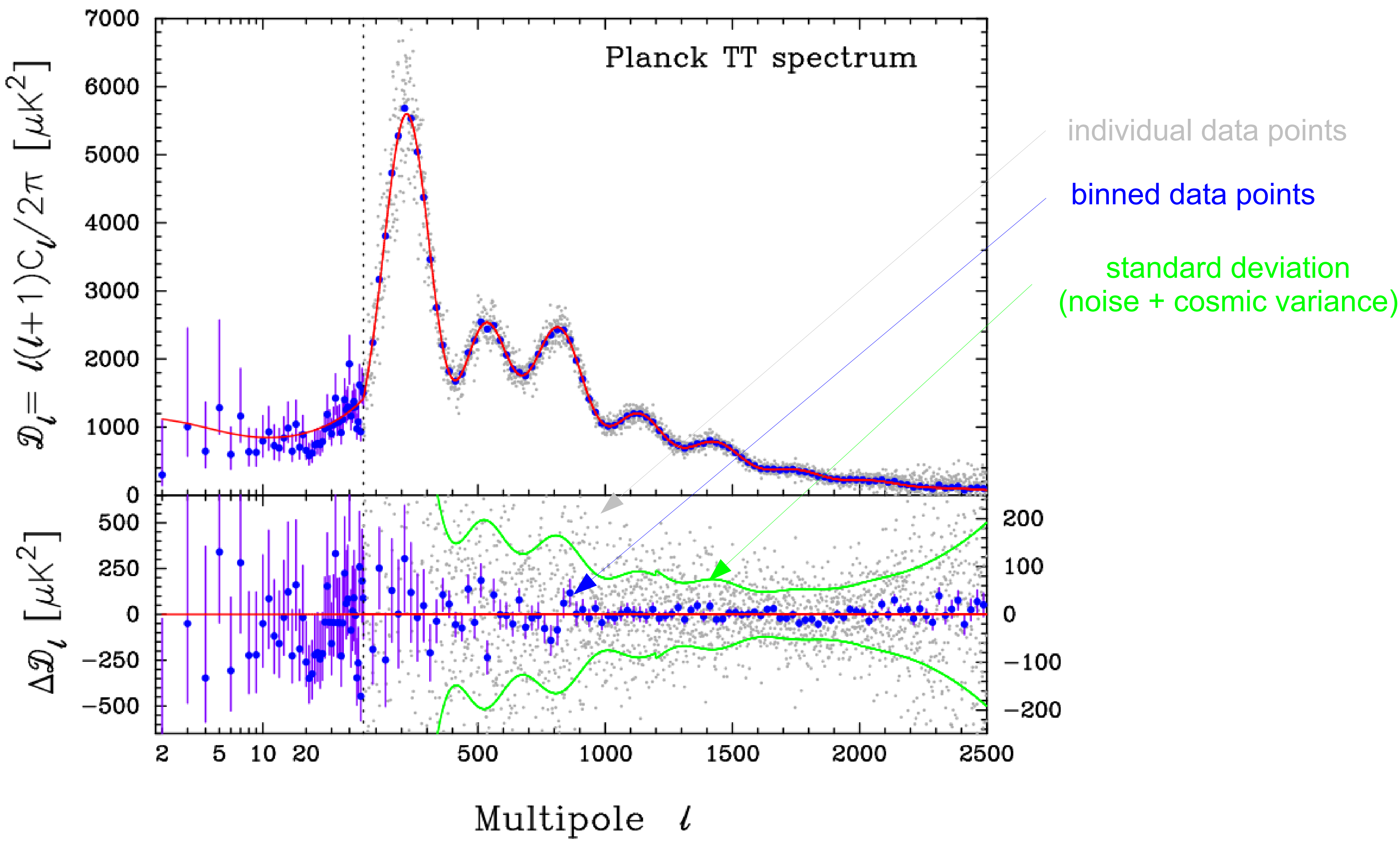
🙄

The cosmological “standard” (ΛCDM) model still stands strong

☺

Significant improvements in constraints on nearly all interesting cosmological parameters

Planck (temperature) angular power spectrum



individual data points

binned data points

standard deviation
(noise + cosmic variance)

Goodness-of-fit of ΛCDM

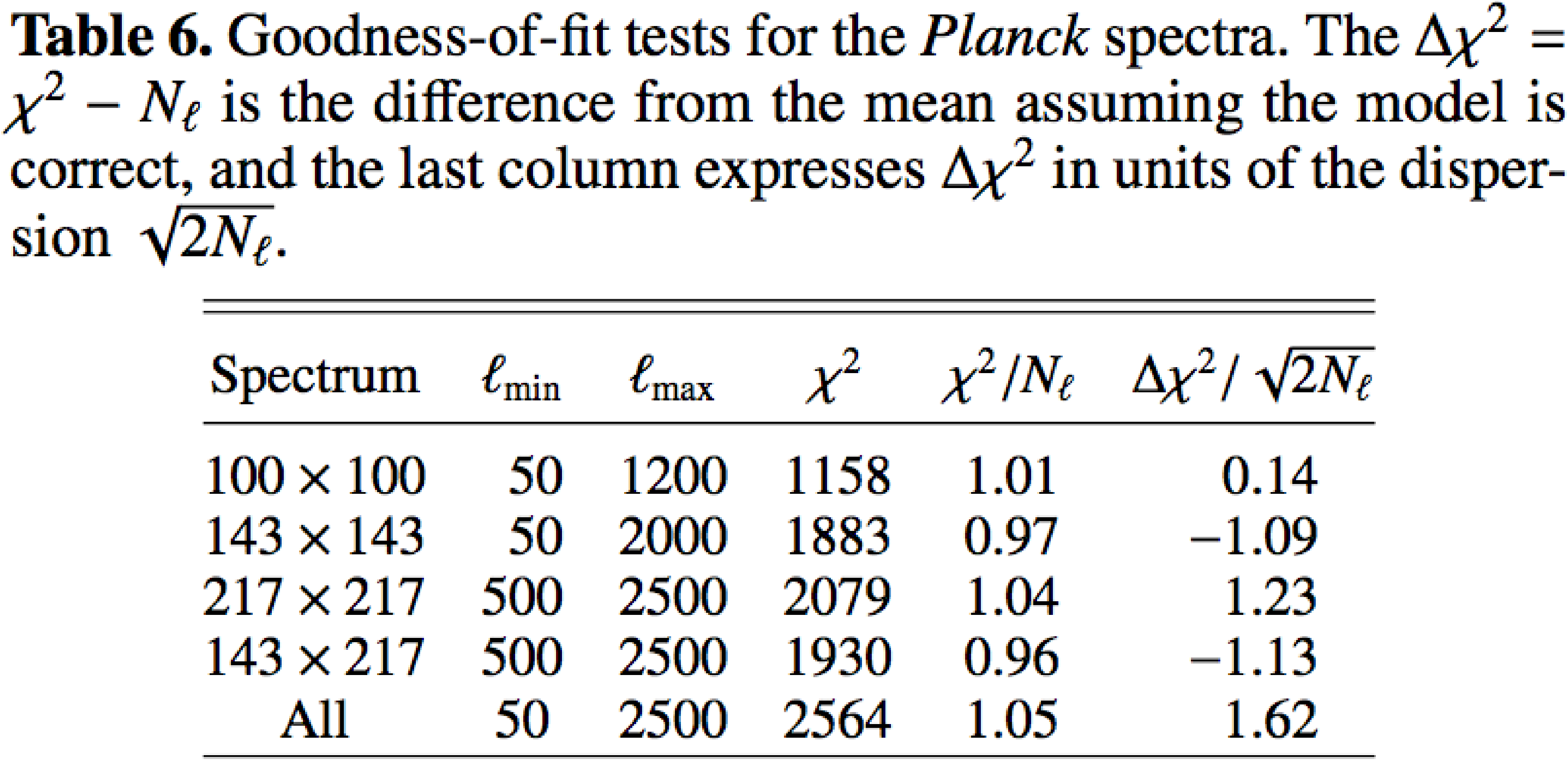


Table 6. Goodness-of-fit tests for the *Planck* spectra. The $\Delta\chi^2 = \chi^2 - N_\ell$ is the difference from the mean assuming the model is correct, and the last column expresses $\Delta\chi^2$ in units of the dispersion $\sqrt{2N_\ell}$.

Spectrum	$\ell_{\rm min}$	$\ell_{\rm max}$	χ^2	χ^2/N_ℓ	$\Delta\chi^2/\sqrt{2N_\ell}$
100×100	50	1200	1158	1.01	0.14
143×143	50	2000	1883	0.97	−1.09
217×217	500	2500	2079	1.04	1.23
143×217	500	2500	1930	0.96	−1.13
All	50	2500	2564	1.05	1.62

Different models/data combinations: “the grid”

- Basic ΛCDM model plus eighteen different extensions
- Each of them fit with up to thirty-four combinations of Planck with external data sets
- Almost 400 pages of tables with parameter constraints
- Available online under:

`http://www.sciops.esa.int/index.php?project=planck&page=Planck_Legacy_Archive`

- CMB data alone show no preference for extended models!

The ΛCDM model

Six cosmological parameters:

Hubble parameter

Cold dark matter density

$$A_{\mathrm{s}}, n_{\mathrm{s}}, H_0, \omega_{\mathrm{b}}, \omega_{\mathrm{c}}, \tau$$

Amplitude of initial fluctuations

Spectral index of initial fluctuations

Baryon density

Optical depth to reionisation

plus another 14 “nuisance” parameters for Planck data, describing

- perturbations from
  - the cosmic infrared background (4)
  - unresolved point sources (4)
  - the Sunyaev-Zeldovich effect (3)
- beam shape uncertainties (1)
- relative calibration uncertainties (2)

So what about neutrinos?

Cosmological neutrinos

Cosmic neutrino background

(decoupling at T ~ 1 MeV)

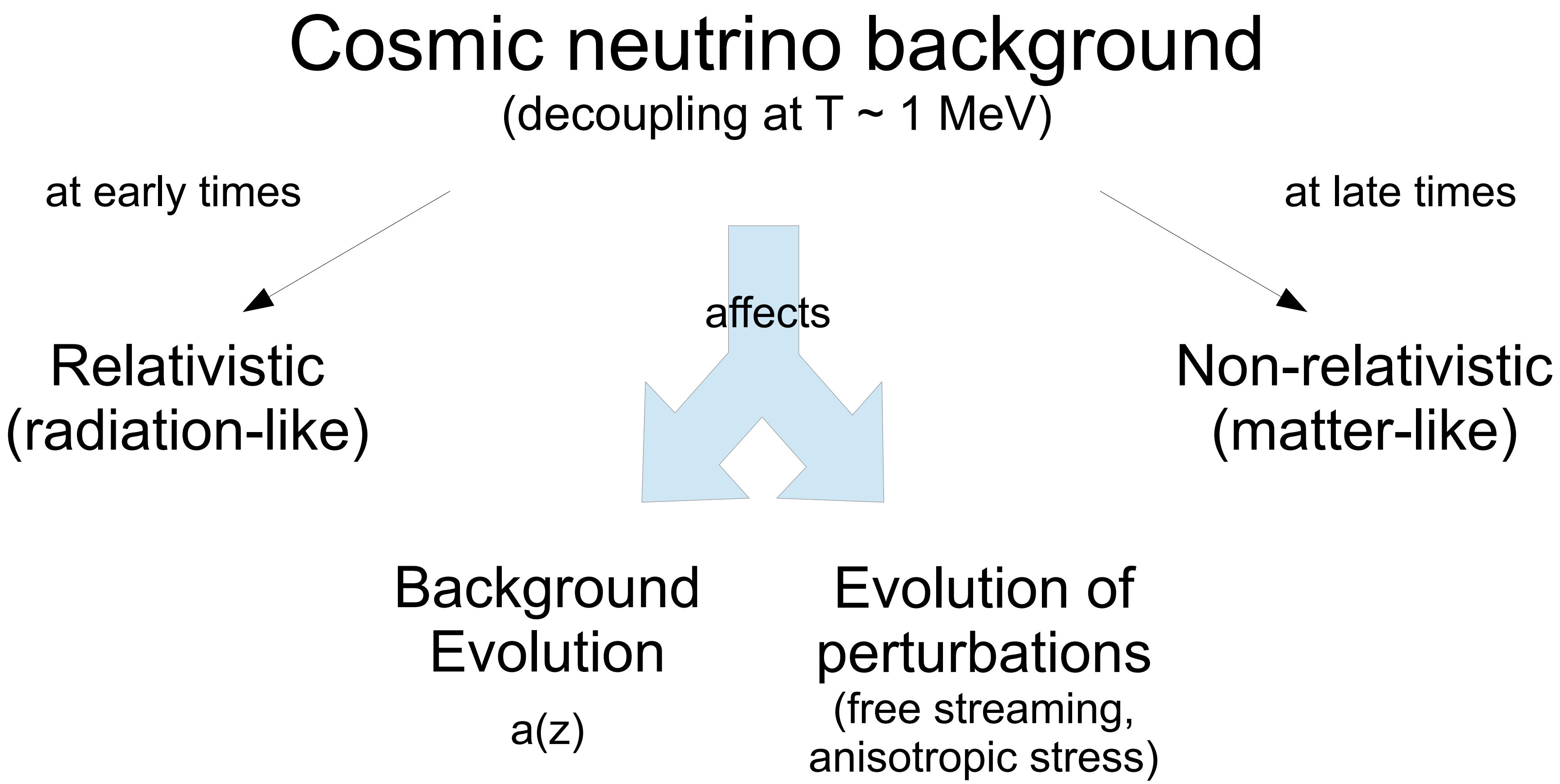
at early times

Relativistic
(radiation-like)

at late times

Non-relativistic
(matter-like)

Cosmological neutrinos



Cosmic neutrino background
(decoupling at T ~ 1 MeV)

at early times

at late times

Relativistic
(radiation-like)

Non-relativistic
(matter-like)

affects

Background
Evolution

a(z)

Evolution of
perturbations
(free streaming,
anisotropic stress)

Cosmological neutrinos

Cosmic neutrino background

(decoupling at T ~ 1 MeV)

at early times

Relativistic
(radiation-like)

affects

at late times

Non-relativistic
(matter-like)

Background
Evolution

$a(z)$

Evolution of
perturbations
(free streaming,
anisotropic stress)

These are purely gravitational effects which do not care about “neutrinoness” at all!

Cosmological neutrinos: parameters

How much energy density do “neutrinos” contribute

at early times?

at late times?

photon
energy density

Fermi-Dirac
vs. Bose-Einstein

lower neutrino
temperature

$$\rho_{\mathrm{r}} = \rho_\gamma \left[1 + N_{\mathrm{eff}} \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} \right]$$

radiation
energy density

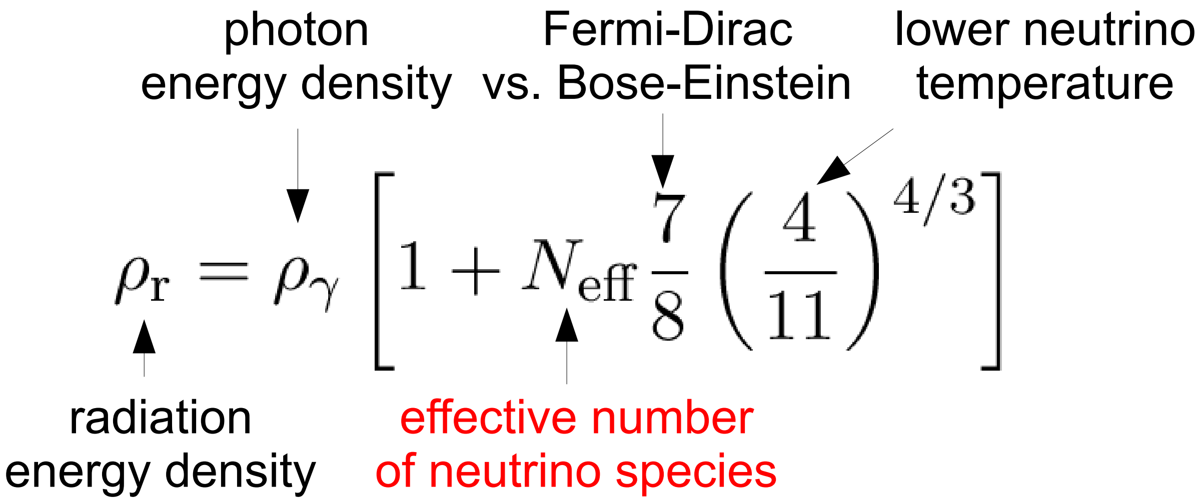
effective number
of neutrino species

Standard model/ΛCDM: $N_{\mathrm{eff}} = 3.046$

Cosmological neutrinos: parameters

How much energy density do “neutrinos” contribute

at early times?



photon energy density

Fermi-Dirac vs. Bose-Einstein

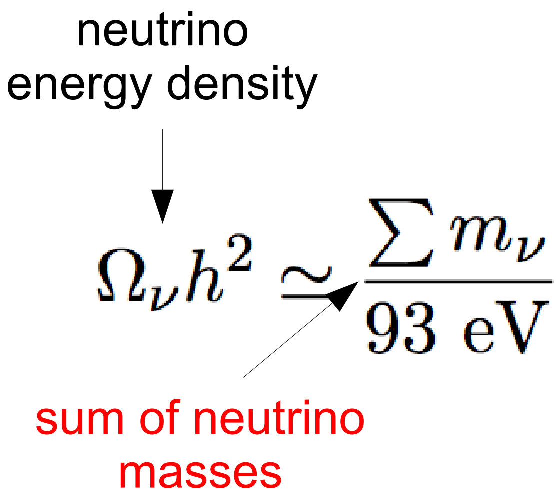
lower neutrino temperature

$$\rho_{\rm r} = \rho_\gamma \left[1 + N_{\rm eff}\,\frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\right]$$

radiation energy density

effective number of neutrino species

at late times?



neutrino energy density

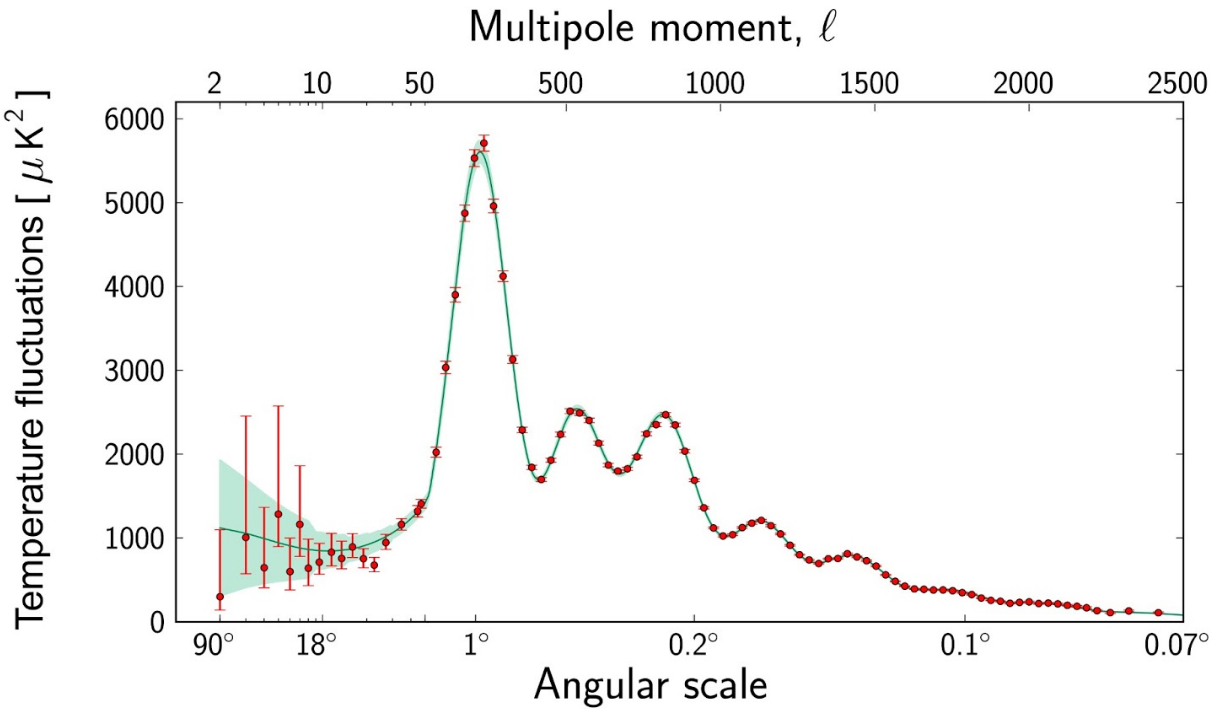
$$\Omega_\nu h^2 \simeq \frac{\sum m_\nu}{93\ \mathrm{eV}}$$

sum of neutrino masses

Standard model/ΛCDM: $N_{\rm eff} = 3.046$

ΛCDM: $\sum m_\nu = 0.06$ eV

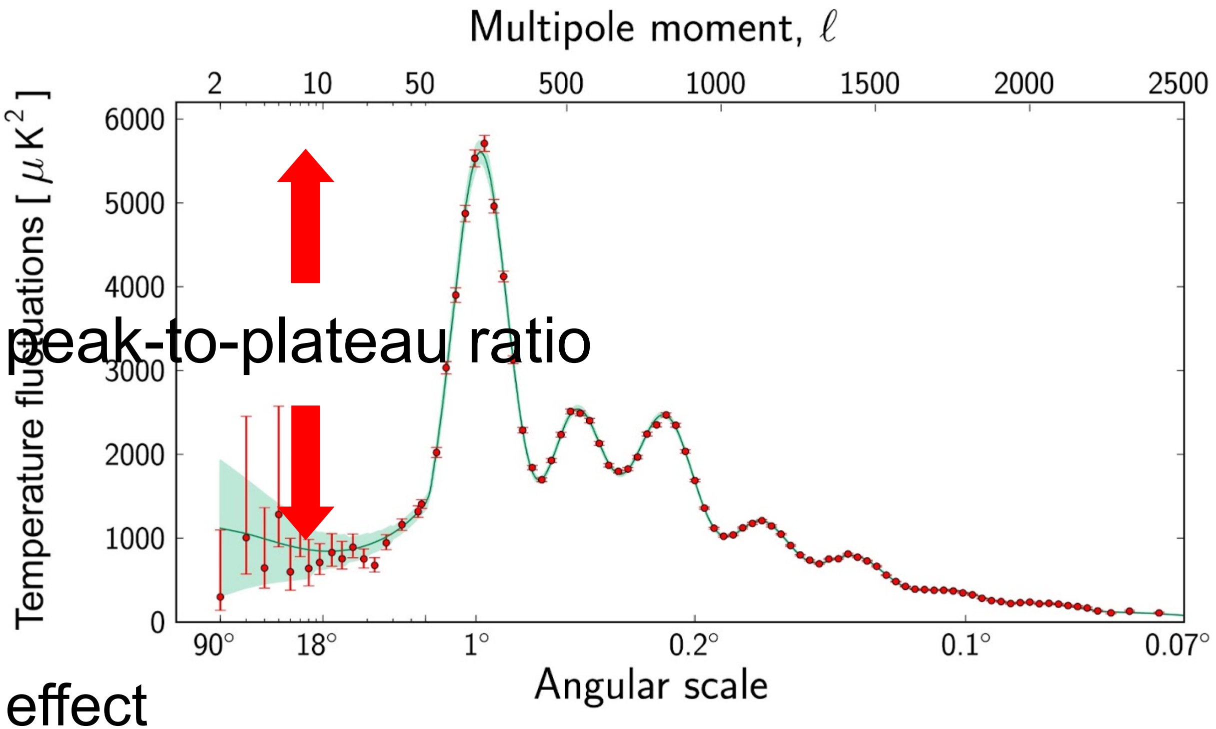
Neutrino parameters:
understanding degeneracies



- Parameters must be inferred from CMB power spectrum
- Adding parameters often introduces parameter degeneracies
- To understand degeneracy directions, look at parameter combinations that leave broad features of the spectrum unchanged

[e.g., Bashinsky & Seljak 2003; Lesgourgues et al. 2013; Archidiacono et al. 2013]

Neutrino parameters:
understanding degeneracies



peak-to-plateau ratio

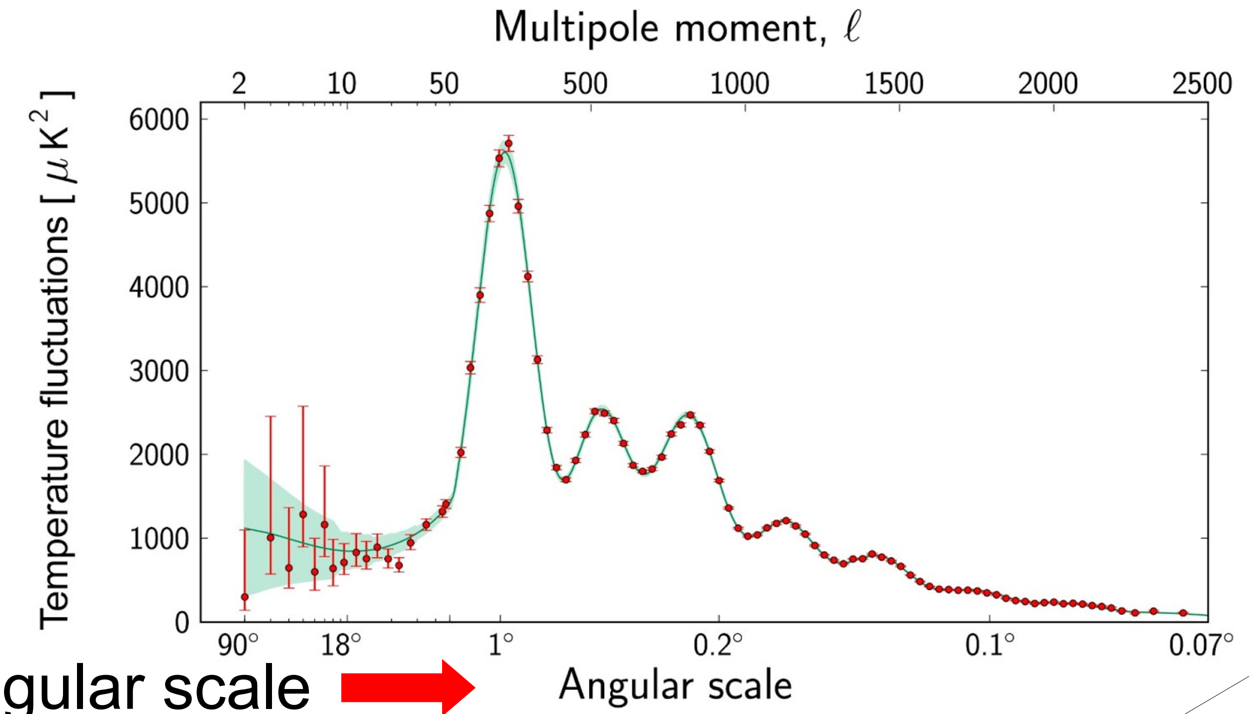
via early ISW effect
related to redshift of
matter-radiation equality

Matter density

$$1 + z_{\mathrm{eq}} = \frac{\omega_{\mathrm{m}}}{\omega_\gamma} \frac{1}{1 + 0.2271 N_{\mathrm{eff}}}$$

Photon energy density

Neutrino parameters:
understanding degeneracies



1st peak angular scale

$$\theta_s \equiv r_s(z_\star)/D_A(z_\star)$$

Redshift of decoupling

Sound horizon

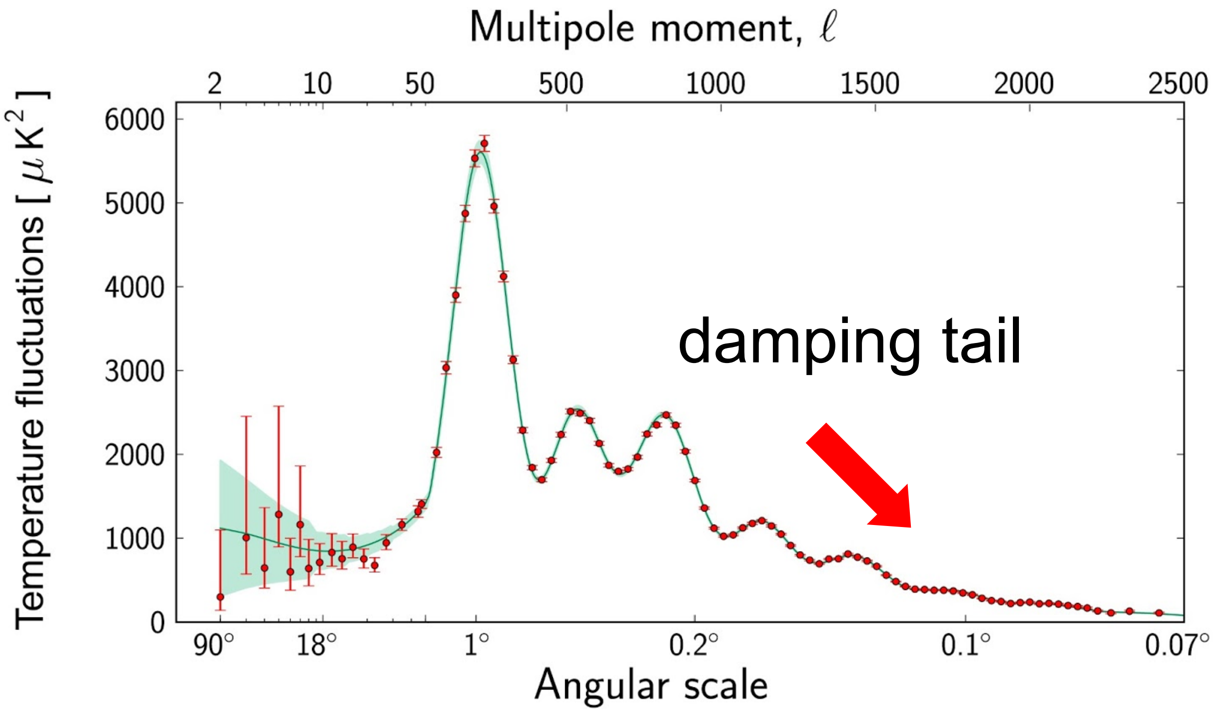
Sound speed

$$r_s(z_\star) \equiv \int_{z_\star}^{\infty} dz \, \frac{c_s(z)}{H(z)}$$

$$D_A(z_\star) \equiv \int_0^{z_\star} \frac{dz}{H(z)}$$

Angular diameter distance

Neutrino parameters:
understanding degeneracies



$$\theta_{\rm d} \equiv r_d(z_\star)/D_{\rm A}(z_\star)$$

Photon diffusion scale

Accidental approximate degeneracy with n_s!

Neutrino parameters:
main degeneracy directions

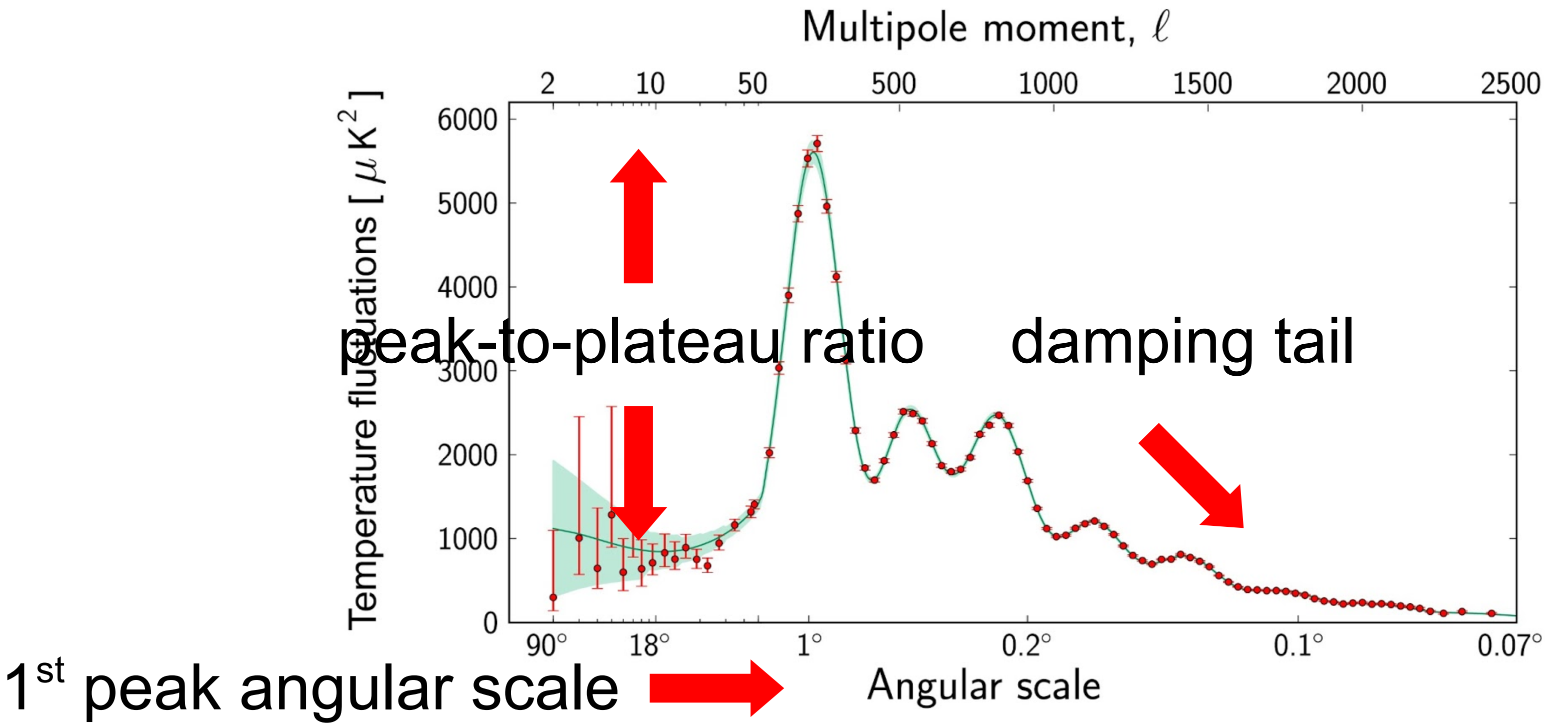
Increasing N_{eff} ...

- increases ω_m
- increases H_0
- increases n_s

Increasing $\sum m_\nu$ ...

- does not affect ω_m much
- decreases H_0
- decreases n_s

Why are non-CMB data sets important?



peak-to-plateau ratio

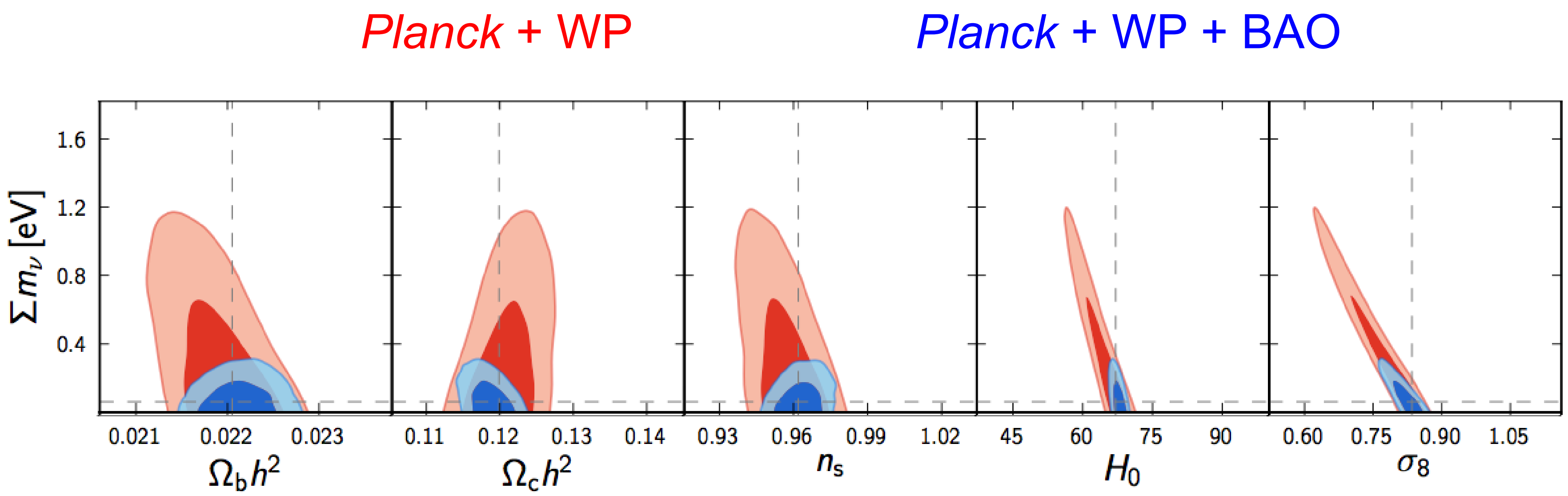
damping tail

1st peak angular scale

- In ΛCDM, these three observables essentially depend only on ω_m, H_0 and n_s
- In extended models, often a dependence on a fourth parameter (e.g., neutrino mass, number of neutrinos, curvature, etc.) → unconstrained direction
- External data (BAO, clusters, HST, lensing) can break degeneracy

Constraints from
Planck temperature
+ WMAP large scale polarisation
(+ ACT/SPT small scale temperature)
(+ Baryon Acoustic Oscillation)
data

Neutrino mass constraints

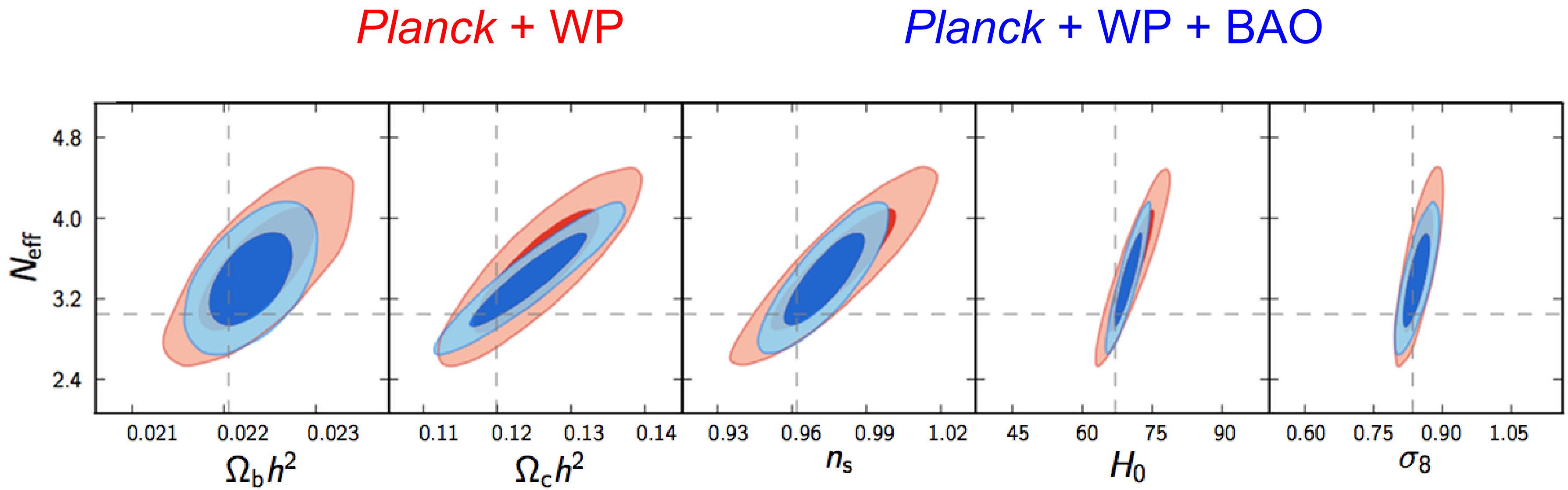


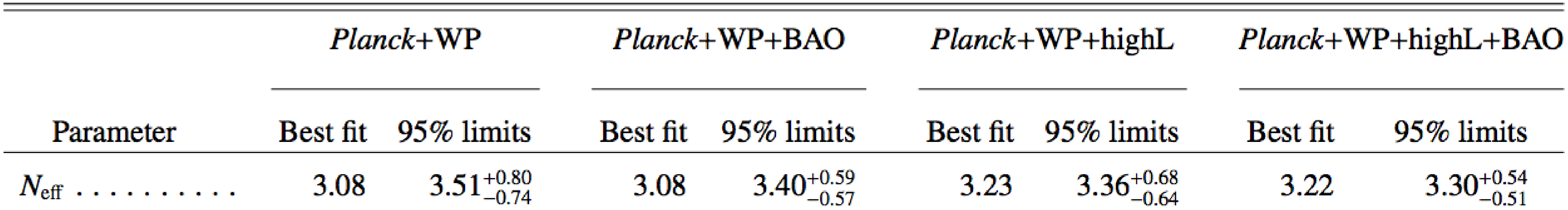
	Planck+WP		*Planck*+WP+BAO		*Planck*+WP+highL		*Planck*+WP+highL+BAO	
Parameter	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits
Σm_ν [eV]	0.022	< 0.933	0.002	< 0.247	0.023	< 0.663	0.000	< 0.230

No evidence for neutrino masses

[Planck 2013 results XVI]

Effective number of neutrino species



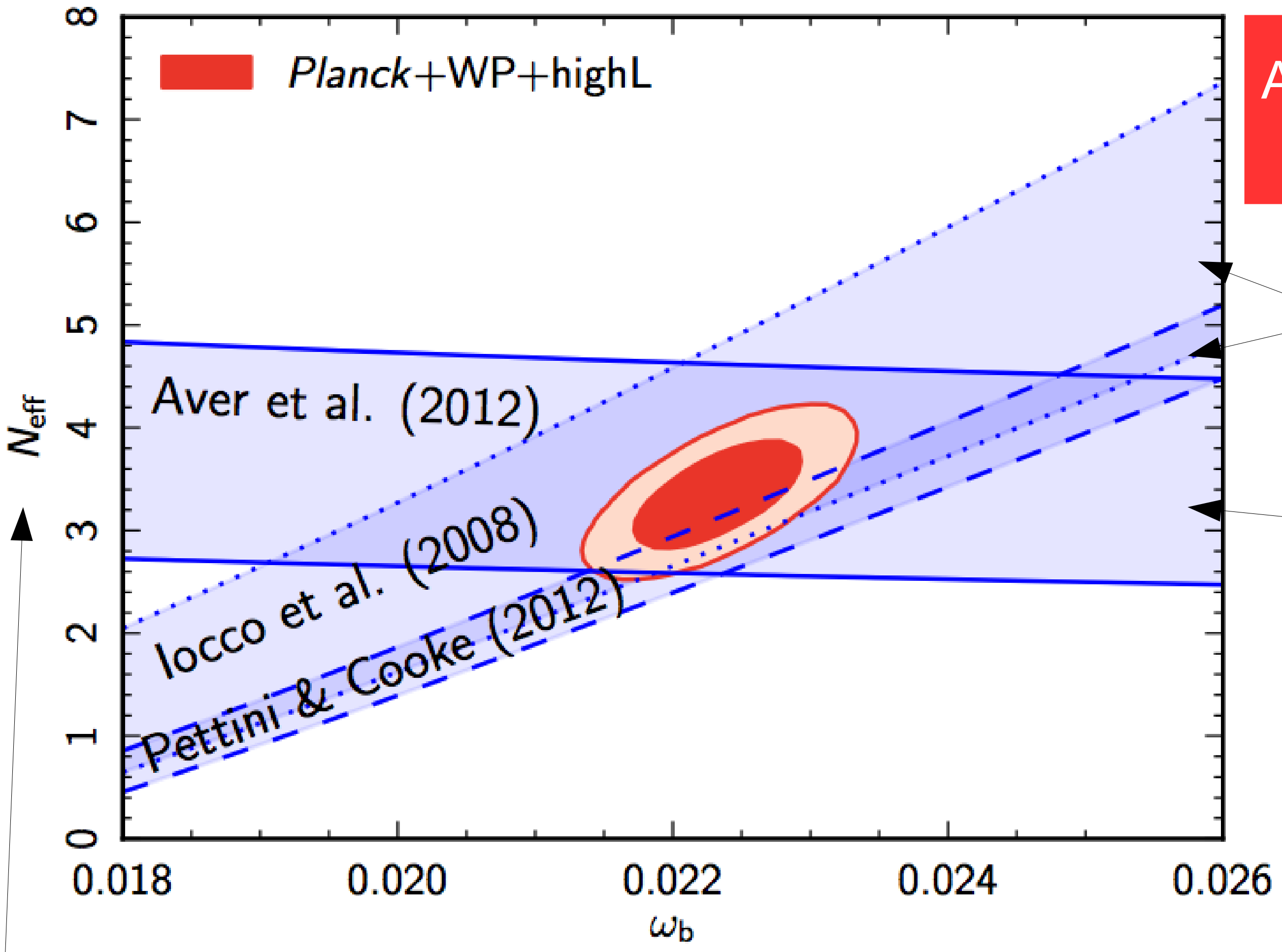


	Planck+WP		*Planck*+WP+BAO		*Planck*+WP+highL		*Planck*+WP+highL+BAO	
Parameter	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits
N_{eff}	3.08	$3.51^{+0.80}_{-0.74}$	3.08	$3.40^{+0.59}_{-0.57}$	3.23	$3.36^{+0.68}_{-0.64}$	3.22	$3.30^{+0.54}_{-0.51}$

No evidence for extra (“dark”) radiation,
but overwhelming evidence for existence of “neutrino” background

[Planck 2013 results XVI]

Consistency with BBN and primordial element abundances



Astrophysically measured element abundances

Deuterium abundance
+ BBN

Helium abundance
+ BBN

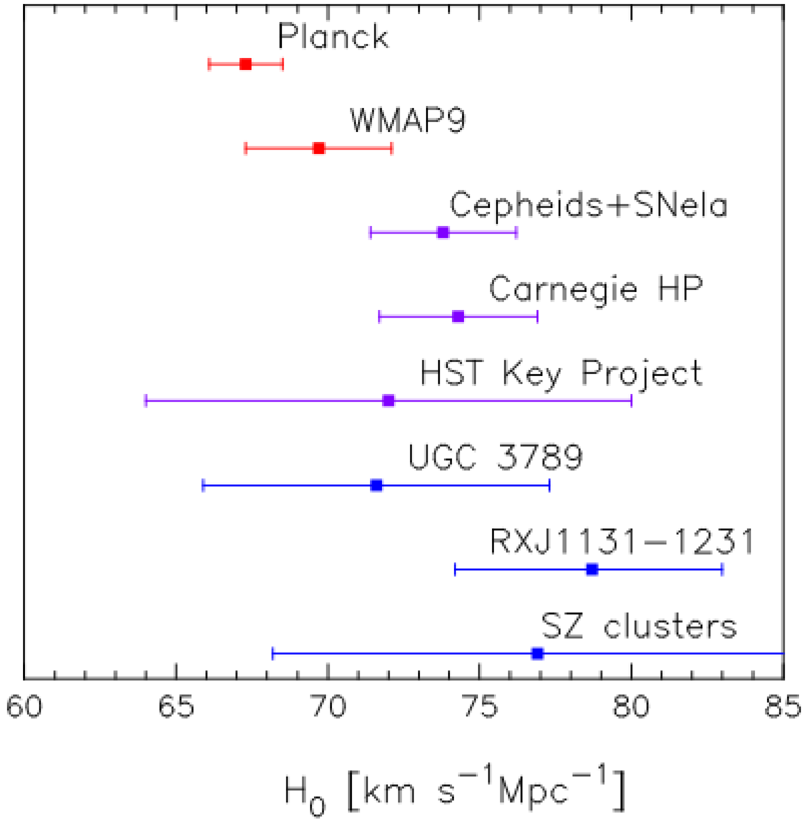
Effective number
of neutrino species

Baryon density

[Planck 2013 results XVI]

Discrepancies (?)

- Local measurements of the Hubble parameter



In ΛCDM, CMB seems to prefer too small
Values of the Hubble parameter?

Discrepancies (?)

- Cluster counts:

rms amplitude of
matter perturbation
at scale of 8 h^{-1} Mpc

$$\sigma_8 \left(\Omega_\mathrm{m}/0.27\right)^{0.3} = 0.782 \pm 0.010$$

Planck clusters
+ X-ray

$$\sigma_8 \left(\Omega_\mathrm{m}/0.27\right)^{0.3} = 0.869 \pm 0.023$$

CMB

- Galaxy shear measurements:

$$\sigma_8 \left(\Omega_\mathrm{m}/0.27\right)^{0.46} = 0.774 \pm 0.040$$

CFHTLenS

$$\sigma_8 \left(\Omega_\mathrm{m}/0.27\right)^{0.46} = 0.891 \pm 0.031$$

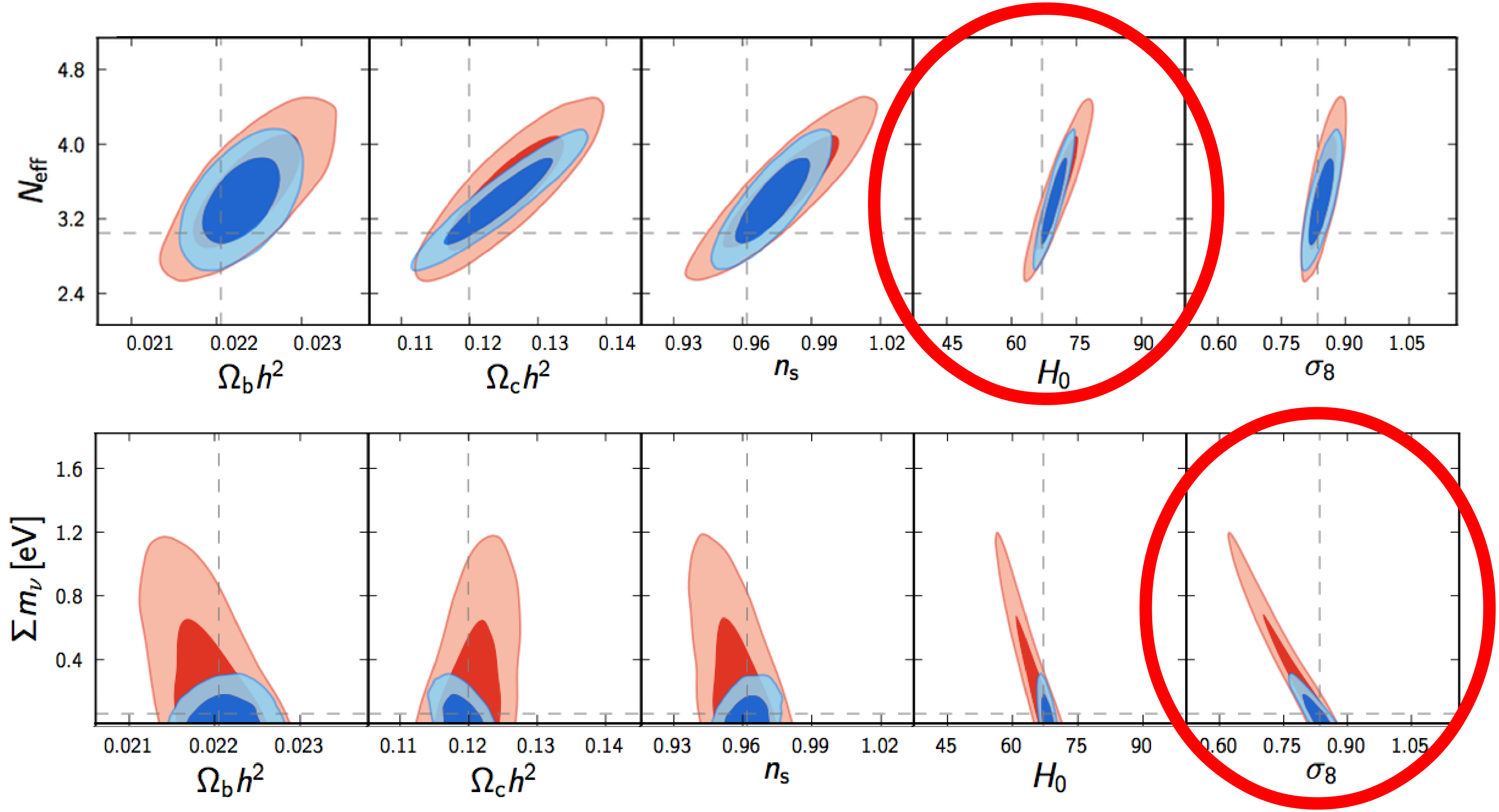
CMB

In ΛCDM, CMB seems to have a preference
for too much power on small scales?

Consistency with other data sets

- Parameter discrepancies could imply underestimated systematical uncertainties or bias in either data set
- Parameters are not directly measured, but rather inferred from the data
  → Discrepancy is model-dependent!
- Are we perhaps looking at the wrong model?
- If so, what model could resolve the discrepancies?

Look at degeneracies



Extra radiation can enhance H_0

Hot dark matter can suppress σ_8

Sterile neutrinos as a solution?

- Consider standard active neutrinos plus additional light particles (could be, e.g., sterile neutrinos)
- Characterised by two parameters:
  - Energy density when relativistic: $\Delta N_{\text{eff}} = N_{\text{eff}} - 3.046$
  - Energy density today: $m_{\nu,\,\text{sterile}}^{\text{eff}} \equiv (94.1\,\omega_{\nu,\,\text{sterile}})\,\text{eV}$

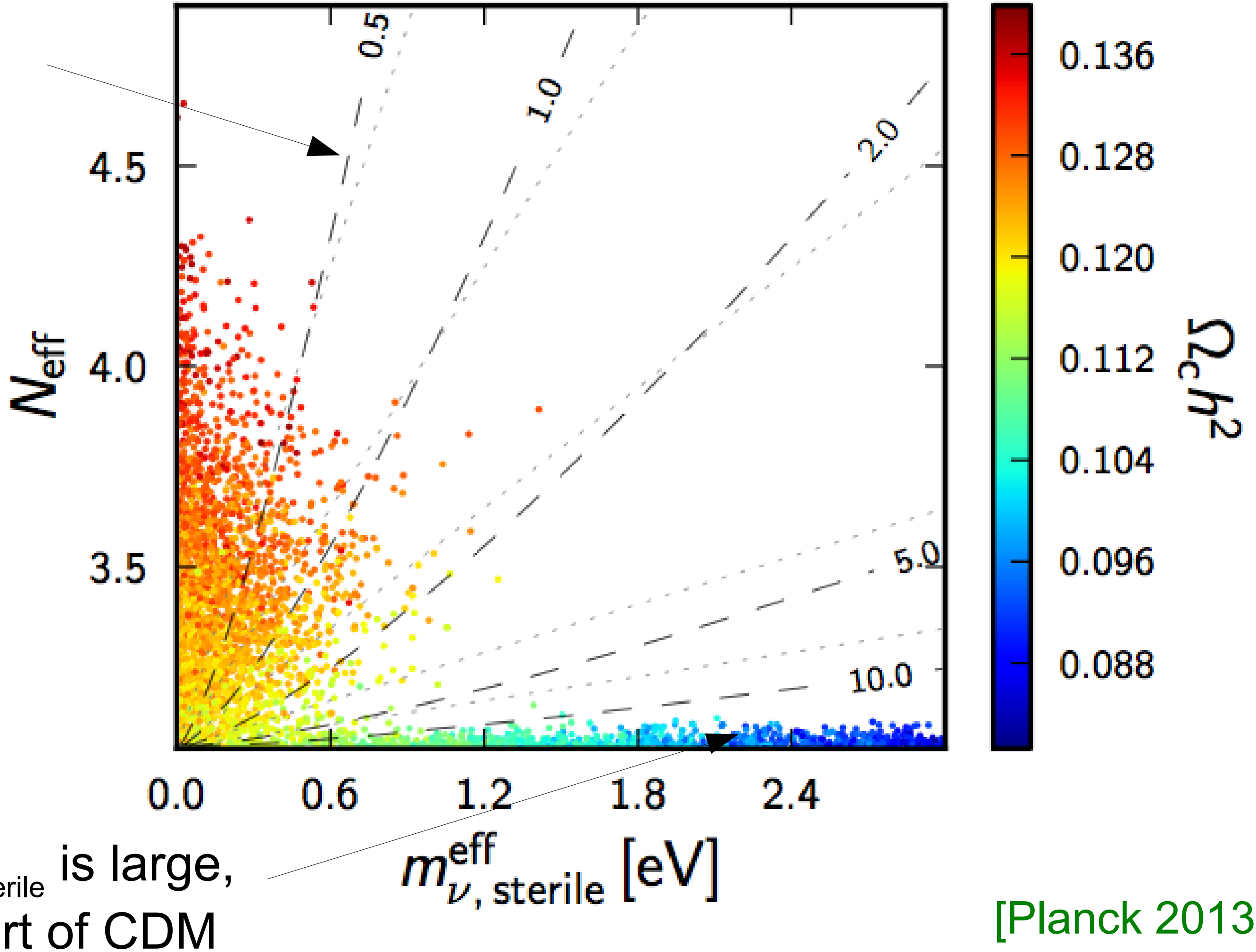
effective mass is equal to
physical mass if $\Delta N_{\text{eff}} = 1$

[Burenin 2013; Wyman, Rudd, Vanderveld & Hu 2013; JH & Hasenkamp 2013; Battye & Moss 2013; Gariazzo, Giunti & Laveder 2013]

Curing discrepancies using hot dark matter?

CMB data only: no evidence

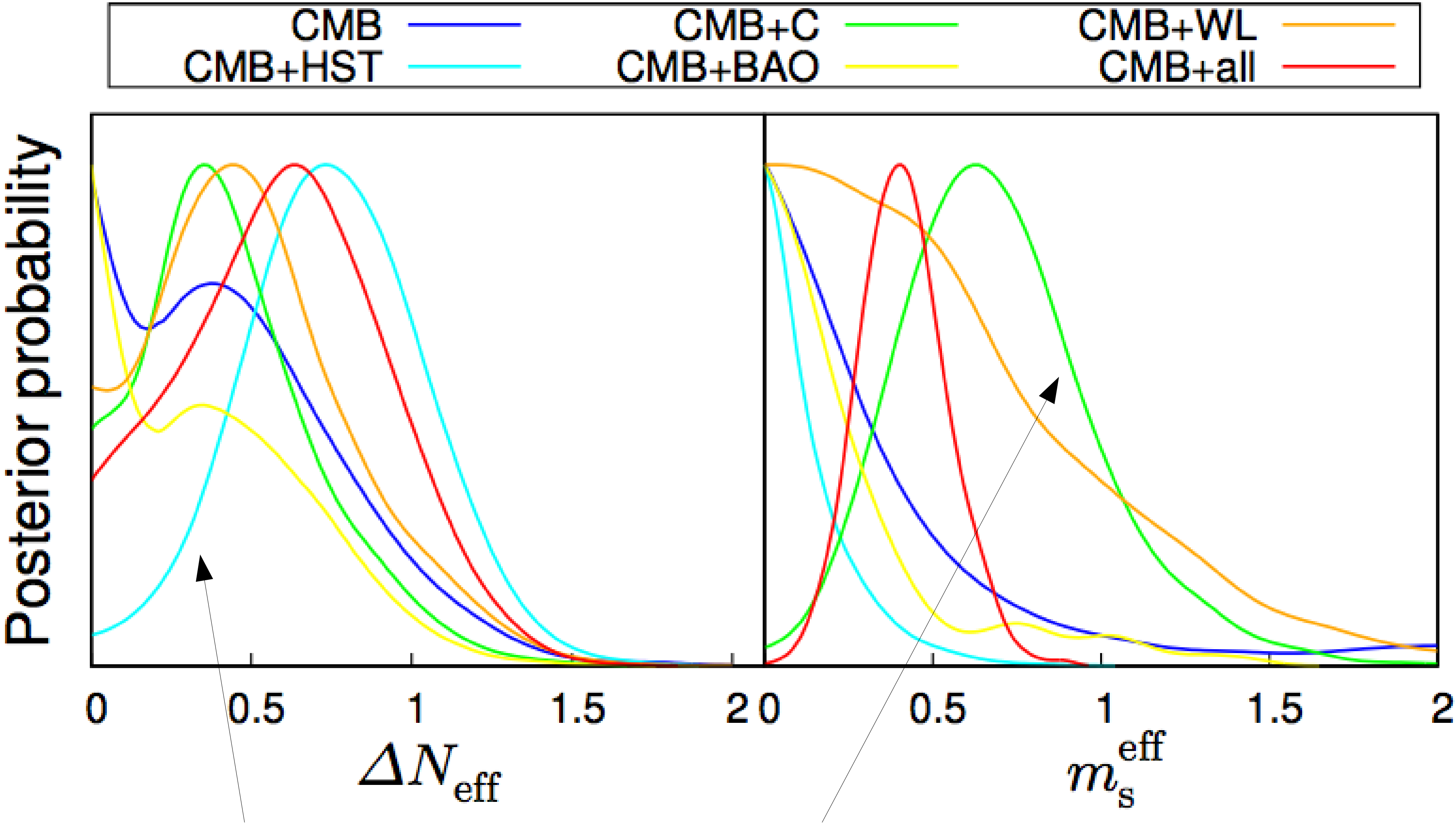
Lines of constant physical m_{sterile}
Dotted: thermal
Dashed: D-W



Physical m_{sterile} is large, replaces part of CDM

[Planck 2013 results XVI]

Curing discrepancies using hot dark matter?



HST pushes $\Delta N_{\mathrm{eff}} > 0$ clusters push $m_s > 0$ [JH, Hasenkamp 2013]

Curing discrepancies using hot dark matter?

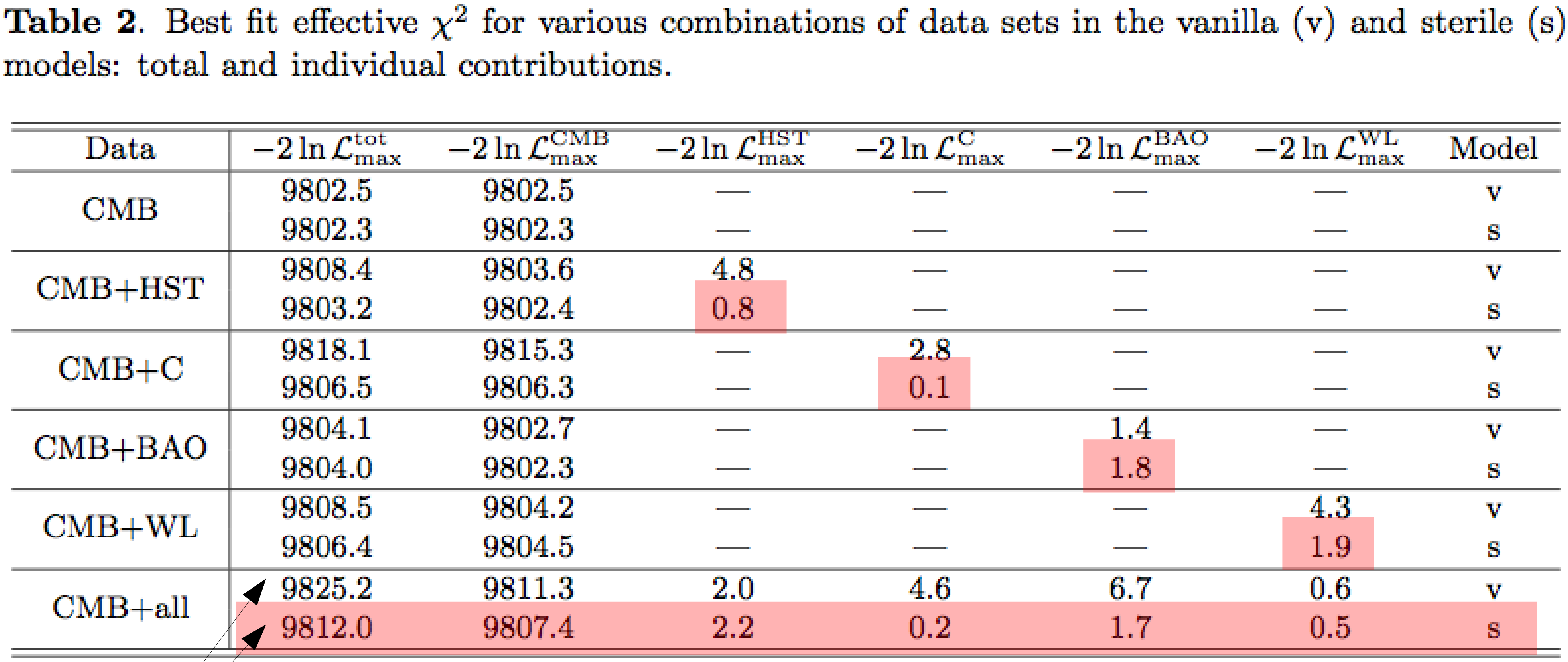


Table 2. Best fit effective χ^2 for various combinations of data sets in the vanilla (v) and sterile (s) models: total and individual contributions.

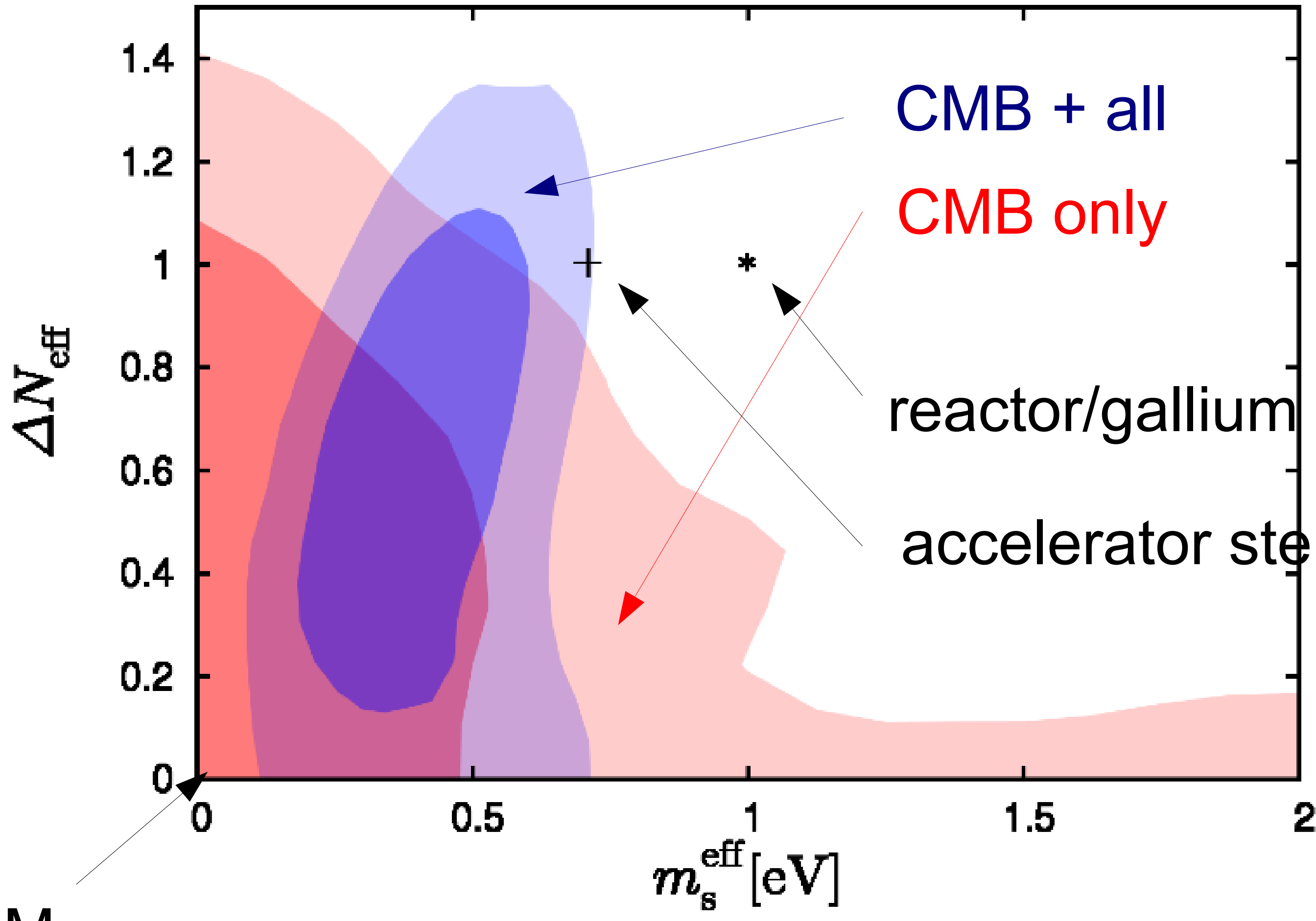
Data	$-2\ln\mathcal{L}^{\rm tot}_{\rm max}$	$-2\ln\mathcal{L}^{\rm CMB}_{\rm max}$	$-2\ln\mathcal{L}^{\rm HST}_{\rm max}$	$-2\ln\mathcal{L}^{\rm C}_{\rm max}$	$-2\ln\mathcal{L}^{\rm BAO}_{\rm max}$	$-2\ln\mathcal{L}^{\rm WL}_{\rm max}$	Model
CMB	9802.5	9802.5	—	—	—	—	v
	9802.3	9802.3	—	—	—	—	s
CMB+HST	9808.4	9803.6	4.8	—	—	—	v
	9803.2	9802.4	0.8	—	—	—	s
CMB+C	9818.1	9815.3	—	2.8	—	—	v
	9806.5	9806.3	—	0.1	—	—	s
CMB+BAO	9804.1	9802.7	—	—	1.4	—	v
	9804.0	9802.3	—	—	1.8	—	s
CMB+WL	9808.5	9804.2	—	—	—	4.3	v
	9806.4	9804.5	—	—	—	1.9	s
CMB+all	9825.2	9811.3	2.0	4.6	6.7	0.6	v
	9812.0	9807.4	2.2	0.2	1.7	0.5	s

$\Delta\chi^2_{\rm eff} = 13.2$

No serious discrepancy remaining
→ can combine data sets

[JH, Hasenkamp 2013]

Curing discrepancies using hot dark matter?



CMB + all

CMB only

reactor/gallium sterile

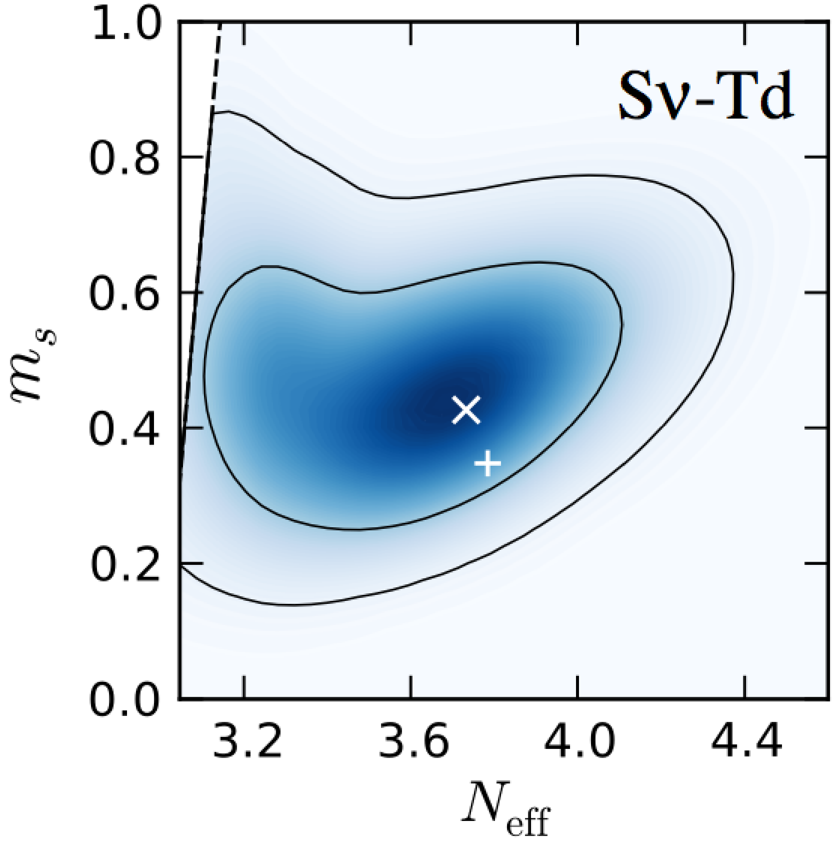
accelerator sterile

ΛCDM

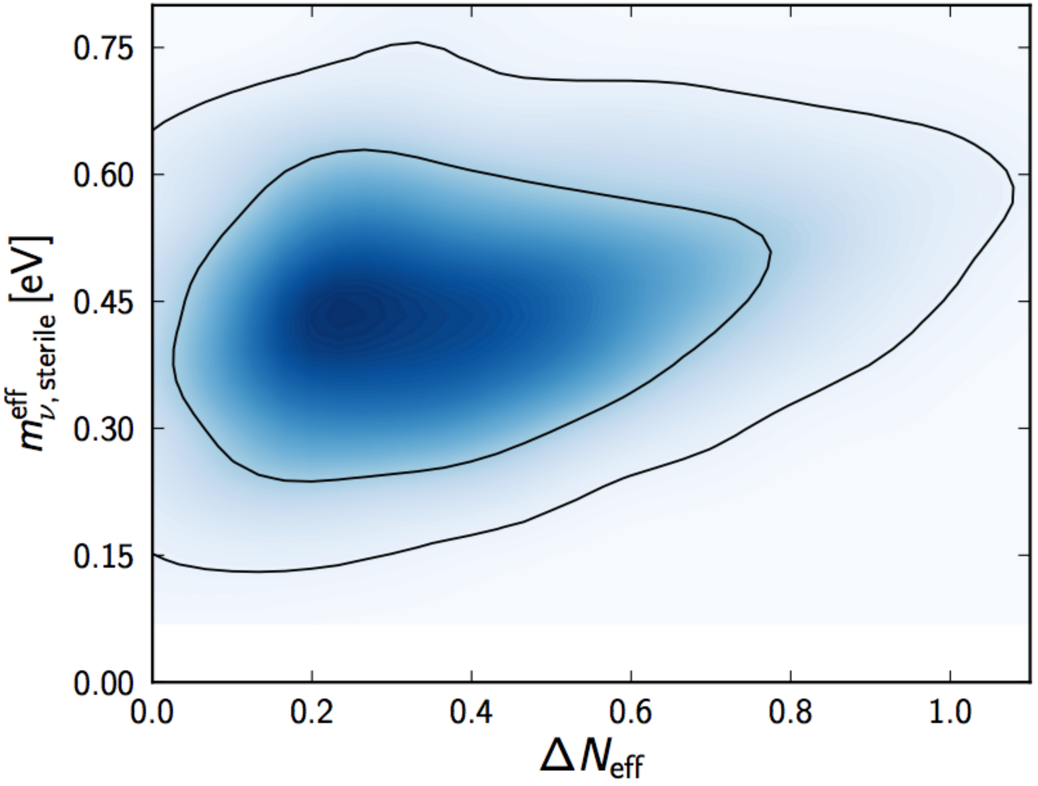
Hints for a hot dark matter component?

(assumption: non-CMB data can be trusted!)

Curing discrepancies using hot dark matter?

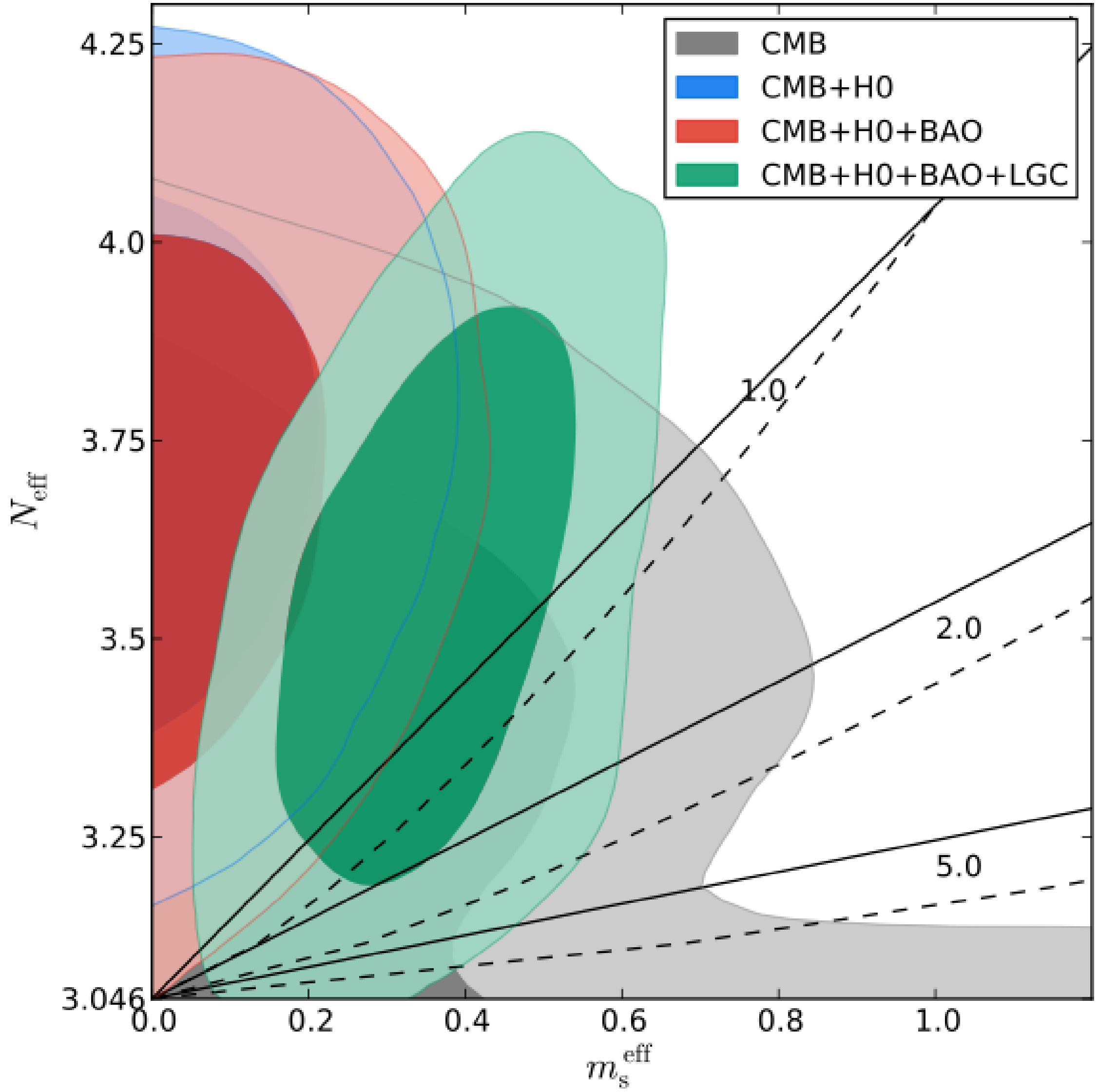


[Wyman, Rudd, Vanderveld & Hu 2013]



[Battye & Moss 2013]

Curing discrepancies using hot dark matter?



[Gariazzo, Giunti & Laveder 2013]

Conclusions

- Planck has delivered an exquisite measurement of the CMB temperature anisotropies, extracting close to the maximum achievable amount of information from this observable
- The ΛCDM model continues to provide an overall very good description of CMB data
- Some discrepancies with non-CMB cosmological data: unknown systematics or sign of new physics?
- Possible to resolve discrepancies with an additional hot dark matter component. Could be interpreted as a light sterile neutrino, but preferred parameter region is not compatible with reactor/accelerator/gallium-preference, unless sterile production can be suppressed
- Planck full mission data (including polarisation data) will be released next year